

## SPECIFICATION

TO ALL WHOM IT MAY CONCERN:

BE IT KNOWN THAT WE, HIROSHI TORIYA, a citizen of Japan residing at Tokyo, Japan, TSUYOSHI HARADA, a citizen of Japan residing at Tokyo, Japan, MAKOTO YAJIMA, a citizen of Japan residing at Tokyo, Japan and REI WAKITA, a citizen of Japan residing at Tokyo, Japan have invented certain new and useful improvements in

# GENERATION OF FREE-FORM SURFACE MODEL BY REVERSIBLE ROUNDING OPERATION

of which the following is a specification:-

## BACKGROUND OF THE INVENTION

## 1. Field of the Invention

The present invention generally relates to a method of generating a free-form surface model based on a reversible rounding operation, a method of generating a lattice polygon model from the generated free-form surface model, a record medium having a program embodied therein for practicing these methods, and a method of transmitting and displaying the free-form surface model.

10 The present invention particularly relates to a method generating a free-form surface model through a perfectly reversible rounding operation where an accurate free-form surface model can be generated.

## 2. Description of the Related Art

15           A shape represented by a lattice polygon model  
is characterized by its simple structure that is easy to  
design. A lattice polygon model can be turned into a  
free-form surface model by a rounding operation. Use of  
the rounding operation makes it possible to readily  
20 generate a free-form surface model by designing a  
lattice polygon model. In the prior art, however, there  
is no known scheme to reconstruct an original lattice  
polygon model from a free-form surface model generated  
therefrom. Once a free-form surface model is generated,  
25 the original lattice polygon model cannot be obtained

from the data of the generated model shape alone,  
thereby preventing reuse of the lattice polygon model to  
create another form.

In a network environment today, transfer and  
5 exchange of 3D data are not performed on a frequent  
basis. A standard representation of 3D shapes that is  
used when transferring 3-dimensional data over a network  
is VRML (Virtual Reality Modeling Language). In VRML,  
data is represented by a set of flat planes that are  
10 polygons. A polygon representation has a drawback in  
that an increase in a level of detail of a represented  
shape requires an increase in data size. In particular,  
data that represents many free-form surfaces requires a  
large number of polygons, resulting in an undesirably  
15 large data size. This discourages transfer of data over  
a network. A further problem is that when polygon-  
representation data is transferred, a displayed shape  
has a level of detail that can be decreased but cannot  
be increased. In this manner, a 3D shape cannot be  
20 represented with sufficient quality if a small data size  
is used, thereby severely discouraging use of 3D data in  
a network environment.

In another field of endeavor, 3D-CAD systems  
used in manufacturing industries use a data-  
25 representation scheme that represents a solid model

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Reversible rounding schemes known to date include those disclosed in: (1) Japanese Patent Laid-open Application No. 9-314697; (2) Atsushi Nakamura, "A Study on Free-form Deformation with Rounding Operation," a Master's Thesis with Keio University, Graduate School of Media and Governance, 1998; and (3) Yuichiro Chaki, "A Study on Flexible Surface Control by Control Lattice," a Master's Thesis with Keio University, Graduate School of Media and Governance, 1998. These schemes are not perfect, however, in that there is a requirement, among others, that all surfaces constituting polygons be coplanar.

25           There is another scheme called a subdivision

surface. This scheme generates a pseudo free-form surface model by subdividing a polygon model. This scheme maintains reversibility, but is only a scheme for generating subdivided polygon models for the purpose of display. This scheme is inherently different from a scheme that generates a precise free-form surface model.

The VRML, which is a representation scheme used in the network environment, is based on use of polygons. As previously noted, a polygon-based representation has a drawback in that as an increased level of detail is pursued, data size inevitably increases. If attempt is made to represent a complex shape with a small amount of data, quality of shape representation is degraded, resulting in a lower display quality.

#### SUMMARY OF THE INVENTION

It is a general object of the present invention to provide a rounding operation that substantially obviates one or more of the problems caused by the limitations and disadvantages of the related art.

It is another and more specific object of the present invention to provide a rounding operation that generates a free-form surface model having the same

5 reconstruction of the original lattice polygon model  
from the generated free-form surface model.

10 model, and matches vertices of the lattice polygon model  
with vertices of the free-form surface model such as to  
allow coordinates of a matched vertex to be obtained  
through linear transformation, followed by generating  
unique control points of curves of the free-form surface  
15 model from the vertices of the free-form surface model,  
thereby attaining a reversible rounding operation.

generated from an externally provided free-form surface  
model. Further, the present invention represents all  
the shapes by interpolated free-form surface data, and  
represents free-form surface structures by abstract  
lattice structures, thereby making it possible to  
represent a 3D shape by a relatively small amount of

data. Moreover, the present invention stores data of  
lattice structures in a server, and provides a client  
with a viewer that interprets a lattice structure and  
displays the lattice structure as free-form surface data  
5 or as detailed polygon-model data that generates a  
polygon model from free-form surface data, thereby  
achieving high-speed 3D-data transfer and display  
thereof.

Other features and advantages of the present  
10 invention will be set forth in the description which  
follows, and in part will become apparent from the  
description and the accompanying drawings, or may be  
learned by practice of the invention according to the  
teachings provided in the description. Objects as well  
15 as the features and advantages of the present invention  
will be realized and attained by a rounding operation  
particularly pointed out in the specification in such  
full, clear, concise, and exact terms as to enable a  
person having ordinary skill in the art to practice the  
20 invention.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig.1 is an illustrative drawing showing a  
lattice polygon model;

25 Fig.2 is an illustrative drawing for

Fig.3 is an illustrative drawing showing a  
5 quadrilateral division of the lattice polygon model;

Fig.5 is an illustrative drawing for  
10 explaining how to obtain vertices of a free-form surface  
model;

15            Fig.7 is an illustrative drawing for  
explaining how to determine the free-form surface model;

Figs.9A and 9B are illustrative drawings  
20 respectively showing a lattice polygon model and a free-  
form surface model generated according to the present  
invention;

Fig.10 is a block diagram showing a configuration of a first embodiment according to the present invention;



Fig.11 is a flowchart of a process according to the first embodiment of the present invention;

Fig.12 is a block diagram showing a computer-based implementation of the present invention;

5 Figs.13A through 13D are tables showing data structures used in the present invention;

Fig.14 is an illustrative drawing providing a brief overlook of a second embodiment of the present invention;

10 Fig.15 is an illustrative drawing showing a configuration of a system according to the second embodiment of the present invention.

Fig.16 is an illustrative drawing showing a data structure of shape information included in an XVL file according to the second embodiment of the present invention;

Fig.17 is an illustrative drawing for explaining a rounding coefficient;

20 Figs.18A and 18B are illustrative drawings showing a human model represented in an XVL format and an example of shading display thereof; and

Fig.19 is a drawing showing an example of real model generation.



model where the edges are each represented by a pair of vertices (i.e., a start point and an end point). The start points and the end points are indices to the rows of vertex-coordinate table 200. In the case of a free-  
5 form surface model, pairs of control points that are obtained when transforming a straight-line edge into a cubic Bezier curve are added in the edge-index table 400. These control points are indices to a control-point-coordinate table 500, which is shown in Fig.13D.

10 Fig.10 is a functional block diagram showing a configuration of a first embodiment of the present invention.

A vertex-calculation unit 10 calculates vertices of a free-form surface model that correspond to  
15 vertices of a lattice polygon model referred to in the vertex-coordinate table 200 by the surface-index table 300. Coordinates of these new vertices are calculated from linear transformation of coordinates of original vertices. The coordinates of the vertices of the free-  
20 form surface model are stored in their designated places in the vertex-coordinate table 200.

An edge-determination unit 20 refers to the vertex-coordinate table 200, the surface-index table 300, and the edge-index table 400, and determines edge  
25 geometries of the free-form surface model that

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surfaces A and midpoints D of the edges B are obtained as shown in Fig.2. A center of a surface is derived by obtaining averages of coordinates of the vertices  $V_i$  that make up the surface. When deriving the surface center, weights may be given to the vertices so as to change a position of the surface center C and the midpoints D. As shown in Fig.3, the quadrilateral division of the surfaces A is carried out by drawing lines between the surface center C and the midpoints D of the edges B.

(II) A center F of a given quadrilateral E generated as described above is obtained from the vertices of the given quadrilateral E as shown in Fig.4. As in the case described above, the center F is calculated by obtaining averages of coordinates of the vertices that constitute the quadrilateral where weights may be given to the vertices.

(III) As shown in Fig.5, a polygon H is generated by connecting the centers F of the quadrilaterals around a vertex G of the original lattice polygon model. Then, a center P0 of the vertices of the polygon H is obtained. P0 becomes a vertex of a new surface model corresponding to the vertex G. As in the case described above, the center P0 is calculated by obtaining averages of coordinates of the vertices that







Fig.9B have one-to-one correspondences therebetween in terms of vertices, edges, and surfaces. The inverse rounding operation thus can be applied to the shape shown in Fig.9B to generate the shape shown in Fig.9A.

5           The present invention is not limited to the embodiment described above, but can be applicable by use of a computer system as shown in Fig.12.

          An input unit 1 is comprised of a keyboard, a mouse, a touch panel, etc., and is used for entering  
10 information. An output unit 2 outputs various output information and information entered by using the input unit 1, and is comprised of a display device, a printer, or the like. A CPU 3 executes various programs. A memory 4 stores therein the programs, and, also, serves  
15 as a temporal storage to store information generated during execution of the programs. A memory unit 5 stores therein the programs, data, information generated during program execution, etc. A memory-media driving unit 6 has a memory medium mounted therein for recording  
20 programs and data, and reads the programs and data from the memory medium to supply them to the memory 4 and/or the memory unit 5. The memory-media driving unit 6 may also be used as a temporal storage for data input/output and/or for providing memory space for execution of the  
25 programs.

In such a computer configuration, each function shown in Fig.10 is implemented as a program or a program unit, and is recorded in a memory medium such as a CD-ROM. The CD-ROM is then mounted in a CD-ROM drive of a computer, and each program is loaded into the computer to carry out a corresponding function of the present invention.

The memory medium may be a semiconductor medium such as a ROM, an IC memory card, etc., an optical medium such as a DVD-ROM, an MO, an MD, a CD-R, etc., or a magnetic medium such as a magnetic tape, a flexible disc, etc.

Further, the programs for implementing the functions of the present invention may be provided via a communication medium rather than via a memory medium.

In the following, a second embodiment of the present invention will be described.

Fig.14 is an illustrative drawing providing a brief overview of the second embodiment of the present invention.

In this second embodiment, a lattice structure that is a combination of a lattice polygon model and rounding information is used for representing shape rather than using a polygon structure that roughly approximates an original shape. Use of such a lattice

structure enables free-form surfaces to be represented with high accuracy. Further, such a lattice structure can be transferred over a network because of a small data size thereof. In the first embodiment, a rounding operation generates a free-form surface model from a lattice polygon model alone. In the second embodiment, on the other hand, rounding information about lattice points and edges is provided in addition to the lattice polygon model, so that the rounding operation is applied to the combination of the model and the information, which may be transferred via a network to enable a client PC to process the data. A lattice kernel provided in the PC, which receives a lattice structure via high-speed data transfer, analyzes the lattice structure and generates free-form surface data from the lattice structure. The lattice kernel then displays the free-form surface data by using a detailed polygon model, thereby reconstructing with a high-speed CPU an image that looks real. Hereinafter, this new format is called XVL (extended VRML with lattice). When used on the Internet, the XVL data is attached to an HTML or XML file in the same manner as is VRML data.

Use of XVL achieves such representation and transfer of 3D data as follows.

- (1) Shape is represented by a lattice

structure that is a combination of a lattice polygon  
model and rounding information, so that a 3D shape can  
be represented by a relatively small amount of data  
compared with detailed-polygon data or free-form surface  
5 data.

(2) 3D modeling software is provided with a  
function (i.e., rounding function) to transform a  
lattice structure into a surface structure (i.e., free-  
form surface model), so that a shape having a surface  
10 structure can be readily designed.

(3) A function (i.e., inverse rounding  
function) to transform a surface structure into a  
lattice structure is provided, thereby making it  
possible to transform existing free-form surface data  
15 easily into data in the XVL format.

(4) A viewer has the rounding function built  
therein to transform a lattice structure into a surface  
structure, so that the viewer can analyze an XVL-file  
having a relatively small file size that is easy to  
20 transfer at a high transfer rate, thereby providing a  
basis for high-quality 3D display.

Fig.15 is an illustrative drawing showing a  
configuration of a system according to the second  
embodiment of the present invention.

25 When the XVL format of the present invention

is used for processing shape data, the XVL format requires around one tenth to one twentieth of the data size required in the VRML format. In the case of the second embodiment, the data size may be  $4/3$  times as much as the data size of the first embodiment. Such a small amount of data makes it possible to achieve a high-speed transfer of 3D data that looks real when displayed.

A server 41 includes an XVL input device 51 and an XVL conversion device 52. The XVL input device 51 is used when data in the XVL format is entered. The XVL conversion device 52 generates an XVL file by applying an inverse rounding operation of the present invention to existing free-form surface data. The server 41 delivers XVL files via a network 42. A client PC 43 and a client PC 44 each include an XVL expansion device 53. The client PC 44 is configured to include the XVL input device 51 and the XVL conversion device 52, so that the client PC 44 can attend to conversion of existing free-form surface data or generation of XVL-format data. Each device may be implemented as software.

#### [Representation of XVL]

Fig.16 is an illustrative drawing showing a data structure of shape information included in an XVL

file according to the second embodiment of the present invention.

A lattice polygon model has the same data structure as that described in connection with the first  
5 embodiment. A method of describing a lattice structure (i.e., a lattice polygon model plus rounding information) in a file will be explained below.

A lattice polygon model is represented as normal polygon data (which is referred to herein as  
10 lattice polygon data). Namely, the lattice polygon model is represented by an array including coordinates of vertices that constitute lattice polygons and by an index array that specifies connections between the vertices to represent the lattice polygons. In the XVL  
15 format, rounding information attached to each vertex and each edge is provided in addition to the lattice information, thereby permitting fine control of free-form surface shapes. The rounding information includes an index specifying a vertex and a rounding coefficient  
20 of the indicated vertex with respect to each of the vertices. The rounding information further includes an index specifying an edge (i.e., a pair of indices indicating two end points of the edge), a rounding coefficient of the edge, a start-point rounding vector  
25 (i.e., vector that defines a tangent vector on the side

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of the start point of the edge), and an end-point  
rounding vector (i.e., vector that defines a tangent  
vector on the side of the end point of the edge) with  
respect to each of the edges. Here, the indices each  
5 indicate numbers indicative of array elements in the  
array that includes coordinates of vertices constituting  
the lattice polygon data.

A rounding coefficient of an indicated vertex  
or an indicated edge specifies how close a corresponding  
10 portion of a generated free-form surface shape comes to  
the indicated vertex or to the indicated edge. As the  
rounding coefficient approaches zero, the free-form  
surface shape has the corresponding portion thereof  
closer to the lattice vertex or edge. As the rounding  
15 coefficient becomes larger, the free-form surface shape  
becomes rounder. The start-point rounding vector and  
the end-point rounding vector are used when a lattice  
structure is reconstructed by applying an inverse  
rounding operation to a free-form surface model. These  
20 vectors relate to information about roundness of a cubic  
Bezier curve, and define tangent vectors at the start  
point and the end point of the curve. If a given shape  
model can be converted into a free-form surface model  
comprised of edges that are all represented by either a  
25 cubic Bezier curve or a straight line, such a shape can

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be described in the XVL format. In such a case, the start-point vector and the end-point vector are added to the edge rounding information.

In the following, a process of the second  
5 embodiment will be described with reference to the lattice polygon model shown in Fig.1. This description is provided to supplement the description provided in connection with the first embodiment.

At STEP1 (II) in the first embodiment, a  
10 center point (i.e., a coordinate average) of vertices that constitute a generated quadrilateral is obtained so as to create a new vertex inside the quadrilateral (Fig.4).

The rounding coefficient changes the way the  
15 new vertex is obtained. When the rounding coefficient is specified, a new vertex inside a quadrilateral is obtained, as shown in Fig.17, after changing  $u$  and  $v$  from their standard values 0.5 on the  $u$ - $v$  parameter space of the quadrilateral.

20 When the rounding coefficient of the vertex  $G$  is set to 0.2 (smaller than its standard value), parameters  $u$  and  $v$  of each relevant quadrilateral are each set to 0.2. As a result, a vertex of a free-form surface model generated at the step STEP1 comes closer  
25 to the vertex  $G$ , so that the generated free-form surface



model has a shape closer to the original lattice polygon model. If the rounding coefficient of a vertex is set to a value larger than the standard value, a rounded free-form surface model is generated, having a

5 corresponding vertex farther away from the vertex of the original lattice polygon model compared to when the standard value is used.

If the rounding coefficient of the edge B (i.e., the rounding coefficient of the midpoint D of the

10 edge B) is set to a value smaller than its standard value, parameters  $u'$  and  $v'$  of quadrilaterals relating to the edge B are set to a smaller value. As a result, an edge of a free-form surface model generated at the step STEP1 comes closer to the edge B of the lattice

15 polygon model, so that the generated free-form surface model has a shape closer to the original lattice polygon model. If the rounding coefficient of an edge is set to a value larger than the standard value, a rounded free-form surface model is generated, having a

20 corresponding edge farther away from the edge of the original lattice polygon model compared to when the standard value is used.

[Example]

25 According to the second embodiment of the

present invention, a surface model generated from an original lattice structure that is a lattice polygon model of Fig.9A plus some rounding information may be a shape that adds some roundness or sharpness to the vertices and/or edges shown in Fig.9B. The surface model corresponding to the shape of Fig.9B may undergo the inverse rounding operation, thereby generating the shape of Fig.9A. As the shape of Fig.9A is represented in the XVL format, data size of the output data can be reduced by a significant amount.

Figs.18A and 18B are illustrative drawings showing a human model represented in the XVL format and an example of shading display thereof. The XVL data shown in Fig.18A has a relatively small data size (44 Kbytes in this example), it can be easily transmitted via a network. Based on this lattice polygon model, a surface model is created as shown in Fig.18B. When this function is implemented in a viewer, such a configuration makes it possible to read XVL over a network and attend to 3-dimensional display that looks real in the network environment. Further, when a surface model generated from an XVL format is supplied in a data format that can be used in a RP (Rapid Prototyping) device, a real model as shown in Fig.19 can be created. Further, if data for use in a CAM system is

generated from the surface model, the real model as described above can be further processed for manipulation and changing of shape.

As is apparent from the description provided above, the present invention generates a free-form surface model that has one-to-one correspondences with the original polygon model in terms of vertices, edges, and surfaces, thereby providing a perfectly reversible rounding operation. Since the polygon model and the free-form surface model have the same topology, the free-form surface model can inherit attributes given to the original polygon model. Namely, attributes such as colors and textures provided for the lattice polygon model can be passed on to the free-form surface model. This is one of the advantages that is difficult to attain in the related art.

According to the XVL format of the present invention, data has a lattice structure that includes a surface structure. The XVL format thus has an advantage in that a relatively small data size suffices to represent shape while high quality of data representation is maintained.

According to the XVL format of the present invention, free-form surface shape is represented by interpolating free-form surfaces that are defined by a

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lattice structure, which is a combination of lattice information and rounding information. This approach achieves a certain level of accuracy while reducing a data size. Because of a small data size, use of data in  
5 a network environment is viable. Further, data representation of free-form surfaces provides for application of XVL data in CAD/CAM systems.

Further, the present invention is not limited to these embodiments, but various variations and  
10 modifications may be made without departing from the scope of the present invention.

The present application is in part based on Japanese priority application No. 12-001136 filed on January 6, 2000 with the Japanese Patent Office, the  
15 entire contents of which are hereby incorporated by reference.

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